Mechanisms of Fluid-Mud Interactions Under Waves

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LONG-TERM GOALS

The goals of this project are to investigate the mechanisms for wave dissipation in the presence of bottom mud. There are a variety of possible mechanism for the decay of wave energy as waves propagate over muds; however, they have not all been validated in the field nor quantified in terms of their relative importance and damping rates in the field or the laboratory. Further new mechanisms may be found. Implementation of these mechanisms into numerical models will provide the ability to infer from the sea surface the nature of the bottom material.

OBJECTIVES

We are measuring wave damping due to mud off the coast of Louisiana, quantifying the dynamics of the bottom mechanisms responsible for the dissipation of wave energy. We are examining different mechanisms for the damping of wave energy by bottom mud in the laboratory and through the use of theoretical and numerical models. These damping mechanisms include the direct forcing of the mud by the wave-induced bottom pressure and velocities; indirect forcing through nonlinear surface wave effects (including wave groups); resonant forcing of interfacial waves at the water/mud interface; damping and shear instabilities in the lutocline; and large scale broadband mechanisms that involve a complex sea state and a combination of the above mechanisms.

APPROACH

The approach is three-pronged: a field effort, involving experiments within a mud patch offshore the coast of Louisiana; a laboratory effort, involving examining the above mechanisms in a controlled environment; and a theoretical and numerical approach, with the ultimate objective of providing numerical models that include wave damping over mud.

The field work consists of three field campaigns (2007 pilot study; 2008 main field experiment, 2010 optional experiment) of wave and bottom measurements. The experiments involve the use of a bottom mounted quadrapod that supports acoustical instruments to measure the horizontal and vertical structure of the velocity and concentration of sediment at the bottom. In addition, a surface buoy provides atmospheric measurements, and two tripods at the seaward and landward ends of the experimental area provide estimates of the directional wave spectrum and energy flux into the study

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area. These tripods also have acoustic backscatter devices to measure the thickness and mud layer concentrations. In addition, cores of the seabed have been taken to determine recent depositional history, porosity, and mixing depth.

Laboratory experiments of waves over muds are being made in two experimental facilities. The first is a shaker table that supports a water/mud tank. This small scale tank is oscillated to excite wave motion and then stopped so that the decay of the wave motion can be measured. The second is an 18m long wave tank outfitted with a 10 m long, 10 cm deep mud patch within a false bottom. A string of acoustic wave gages measure the decay of the waves down the tank.

Large-scale phase-resolved Bottom Mud Wave simulation (BMWs) are developed and applied to investigate various mechanisms of fluid-mud interactions under surface waves. BMWs are developed, based on the integration of the theoretical studies, direct numerical and large-eddy simulation developments, tank measurements, and field experiments conducted in this project, for the prediction of wavefield evolution over muddy bottom and topography. BMWs utilizes a direct phase-resolved simulation for nonlinear wavefield evolution over a horizontal length scale of $O(100\ \lambda)$ (~10km) per dimension by integrating through closure modeling wave transformation and dissipation mechanisms obtained at smaller scales ($O(\lambda)$) via asymptotic theory and DNS/LES, cross-calibrated with measurements.

WORK COMPLETED

Field: Two field experiments have been completed and data are being analyzed. Both shipboard measurements (bottom samples) and instrumented array experiments have been carried out.

Theory and Modeling: A model for direct simulation of the waves and mud has been developed. A theory for non-Newtonian mud has been developed. Dissipation mechanisms for the SNOW wave model are implemented as BMWs.

Laboratory: Two experimental series are underway in both the wave tank and a shaker table apparatus.

RESULTS

Field: The shipboard measurements were carried out by MURI investigators from Boston College (BC) and Memorial University (MU). The objectives are to provide information on spatial and temporal variability of seabed characteristics (grain size, porosity, mixing depth and Be-7) and to provide snapshots of cross-shelf suspended sediment and stratification in the water column. The approach is seabed sampling and water column surveys prior to each tripod deployment, turnaround and recovery cruise in both 2007 and 2008. Two transect lines normal to shore (including the tripod line) were repeated each cruise. A total of ten to twelve box core sites and ten to twenty hydrographic stations were sampled during each of the three cruises. Acoustic surveys using CHIRP and dual-frequency echo sounder were carried out along the two transect lines with additional along-shore tie-lines.

Measurable Be-7 activities were generally confined to physically stratified surficial sediments (the upper ~2-6 cm of the seabed) with high water content (porosity >80%), indicating that these sediments were recently deposited and/or remobilized by currents. Changes in spatial distributions of Be-7 inventories, depth of the surface mixed layer, and sediment bulk density between cruises demonstrate that this high-porosity sediment layer (representing 7-20 kg of dry sediment per square meter of seabed) is highly mobile over monthly timescales, in response to wind-wave resuspension and transport associated with cold fronts. The combined observations suggest that sediment is first delivered from fluvial sources to the east following peak river flow in early spring, and then deposited across a wide region extending 10-15 km from the shore. Subsequent sediment resuspension and shoreward transport in the bottom boundary layer (associated with cold front passage) results in occurrence of high Be-7 inventories within 5-10 km of shore, landward of the 10-m isobath.

MURI investigators from the Woods Hole Oceanographic Institution, Boston College and Memorial University deployed an array of 3 tripods on the Western Louisiana shelf from February 13th to April 10th, 2008. The array was located approximately 30 km west of Trinity Shoals and 70 km west of Marsh Island. The outer (9 m water depth) and inner (5 m water depth) tripods contained an upward looking Nortek AWAC (acoustic wave and current) profiler to measure waves, an ABS to measure profiles of suspended sediment and fluid mud concentration, an ADV to measure near bed velocities, and an OBS5 sensor to measure sediment concentration. The 5-m site also contained downward aimed pulse coherent ADCP (RDI Workhorse in Mode 11). The central (7 m water depth) tripod contained the same instrumentation along with a vertical array of three ADVs and an array of downward pointed pulse coherent Doppler sonars (similar to ABS, but with the ability to measure vertical velocity), to image waves on the mud-water interface. A suite of meteorological measurements was also collected near the central site. All instruments produced high-quality data sets, with no issues due to interference from fishing activities or other disasters. There was some biofouling toward the end of each 1-month deployment, but almost all the acoustic data appears usable, and a large portion of the optical data appears uncorrupted.

In contrast to the relatively small riverine discharges of sediment encountered during the pilot experiment of 2007, the 2008 discharge of the Atchafalaya River was approximately double the 1930-2007 average, producing large quantities of new mud on the inner shelf. Near-bottom optical measurements indicate suspended-sediment concentrations exceeding 50 g/l at all three tripod sites, with highest concentrations occurring after periods of maximal significant wave height. High-concentration bottom layers were more persistent during the second half of the deployment period (mid-March to mid-April) even though significant wave heights were generally lower for cold front events compared to the first part of the deployment. This observation is consistent with delivery of fresh, easily resuspended sediment to the inner shelf in early March because of the above-average discharge from the Atchafalaya, followed by redistribution of sediment on the inner shelf with repeated passage of cold fronts through March and April. The observed rapid increase in bottom salinity and stratification immediately following the passage of cold fronts is consistent with the accumulation of resuspended sediments on the shallow inner shelf.

Acoustic backscatter profiler (ABS) measurements showed deposition of 20 cm in 5- to 7-m water depths after each of three wave events with wave heights of near 2 m on the 9 m isobath (Figure 1). While total wave energy dissipation as measured by the AWACs was greatest during the high energy periods, the spatial attenuation rate (Dissipation/Energy Flux, with dimensions of an inverse length scale) was largest after the wave events, as the recently deposited mud layer consolidated from 20 cm to 10 cm thickness (after each of the green vertical lines in Figure 1). The ABS data also showed waves on the lutocline with heights ranging from 10 cm during periods of high total wave energy dissipation to 2 cm during periods of maximum attenuation rate (see Figure 2 for an example of these waves). The amplitude of these waves is much larger than predicted by models for the surface mode (with the wavenumber of the interface mode matching the surface wavenumber, Figure 3) of a two layer system with water over mud with higher density and viscosity. Analysis based on the continuity equation and measurements of orbital velocity decay away from the interface show that these waves have short wavelength (~3 to 4 m) relative to the surface waves (~ 60 m), but oscillate at the same frequency. These observed waves are consistent with the internal mode solutions to the two layer dispersion equation. The dispersion equation also shows that, in the high viscosity, or thin normalized mud layer (mud layer thickness/viscous boundary thickness) regime, the dissipation due to the internal waves with the observed amplitudes can be significantly larger than the dissipation due to the surface mode. Theoretical work is also being conducted to investigate the mechanisms for the formation of these internal mode lutocline waves.

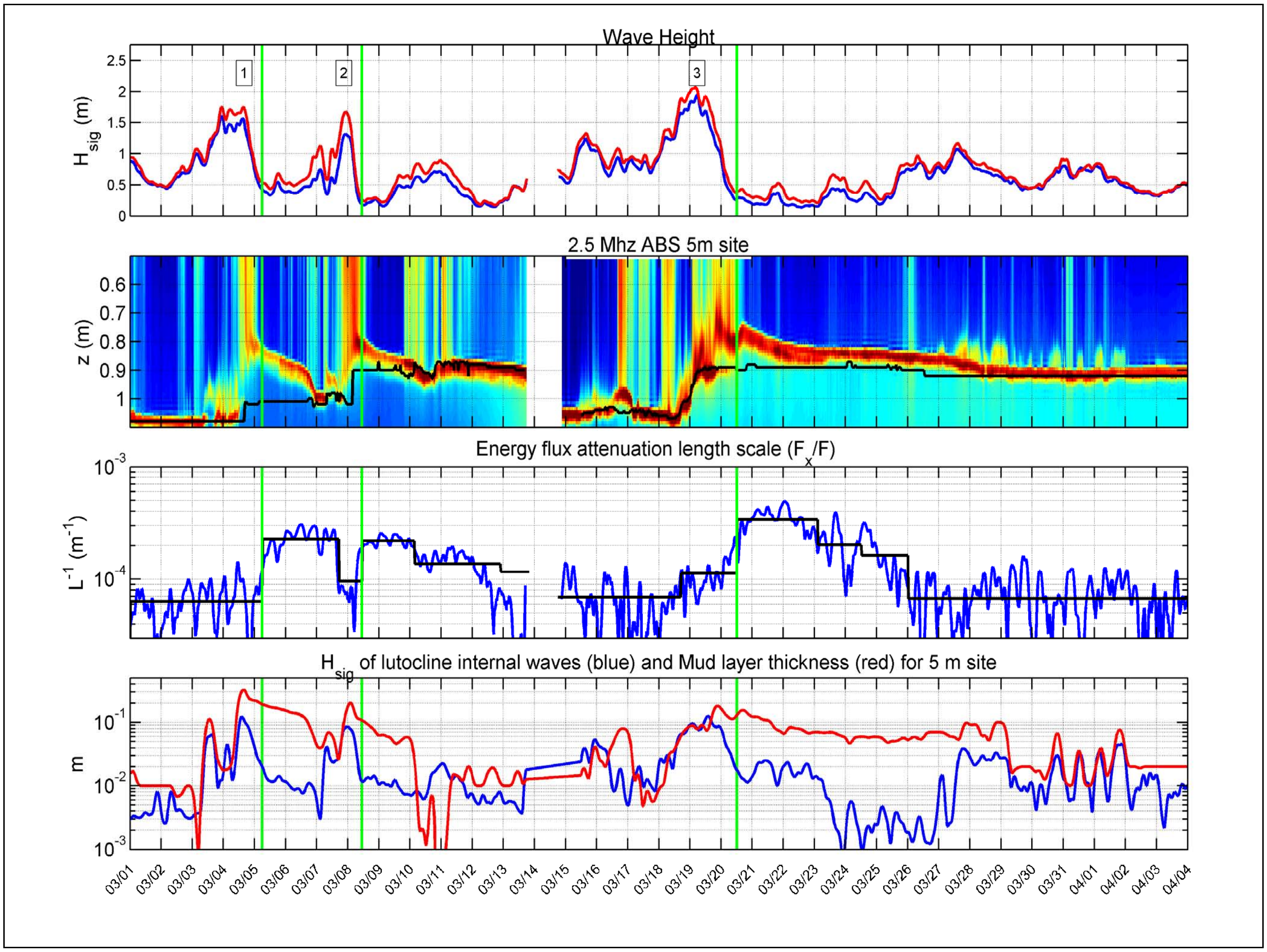


Figure 1 a) Time series of $H_{1/3}$ from the 5 m (blue) and 9 m (red) isobath sites. The three wave events with $H_{1/3} > 1.5$ m are labeled 1, 2 and 3. b) Burst averaged 2.5 MHz ABS data with the consolidated mud bottom, calculated from the 1 MHz ABS data shown as a black line. The color is proportional to backscattered intensity, corrected to account for sediment attenuation in the water column. c) Attenuation F_x/F calculated from the 9 m and 5 m site (blue) and a stepwise low pass fit (black) d) The amplitude of the lutocline waves ($_{0,1/3}$, blue) and the thickness of the mud layer (h_m, red). The vertical green lines indicate the beginning of period of high normalized attenuation coincident with recently deposited mud layers.

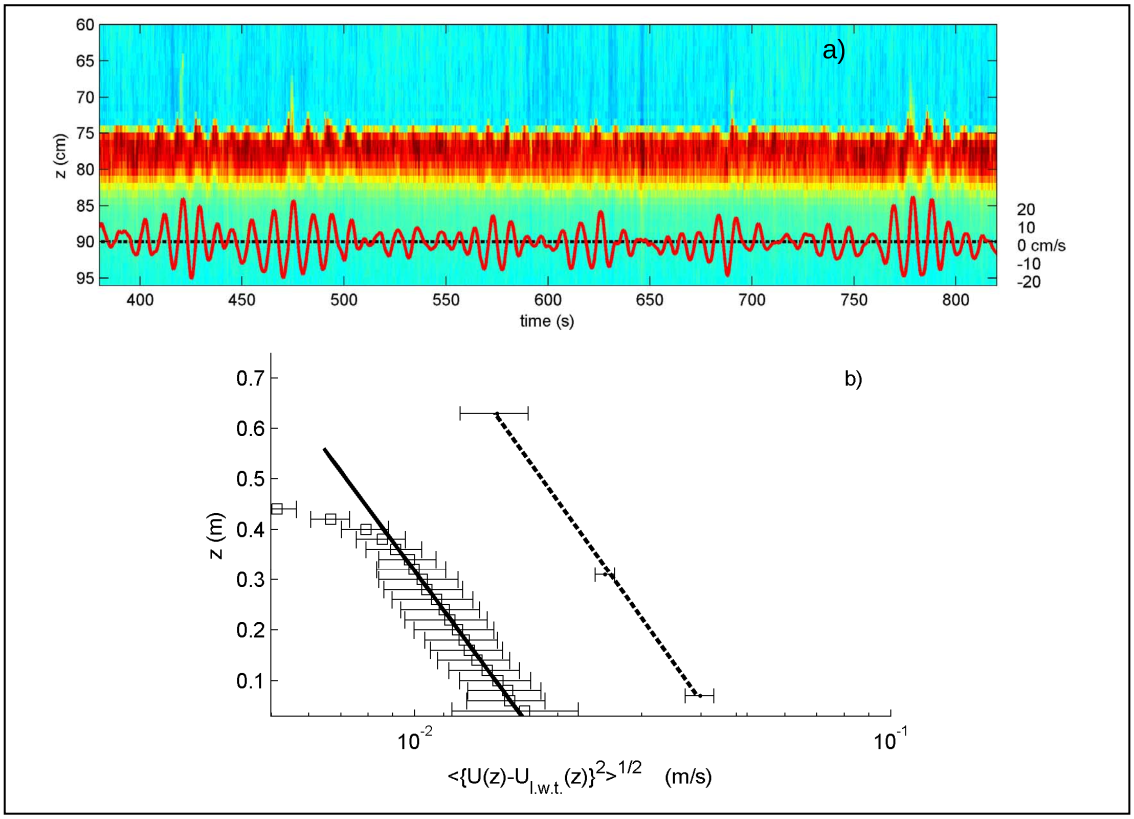


Figure 2. a) 400 seconds of 2 Hz sampled 2.5 MHz ABS data showing $\eta_{1,1/3} = 2$ cm amplitude oscillations on the lutocline. A time series of cross-shore velocity from and ADV located 75 cmab is also shown (red). This data burst was collected on day 35.56 as shown by the green line after event 3 in figure 2. b) Vertical profile of <U(z)-$U_{l.w.t}$(z) > from the 5 m site pulse Coherent ADCP (solid line and squares) for the 5 hourly data bursts proceeding and including that shown in panel a and the vertical array of ADVs at the 7 m site (dashed line and dots). Least squares fits to data from 0.05 m <z < 0.35 m are shown with a mean slope over all bursts of k_{int}= 1.8 m^{-1} and intercept of $u_{0,int}$ = 0.018 m/s for the 5 site and 0.044 m/s for the 7 m site .

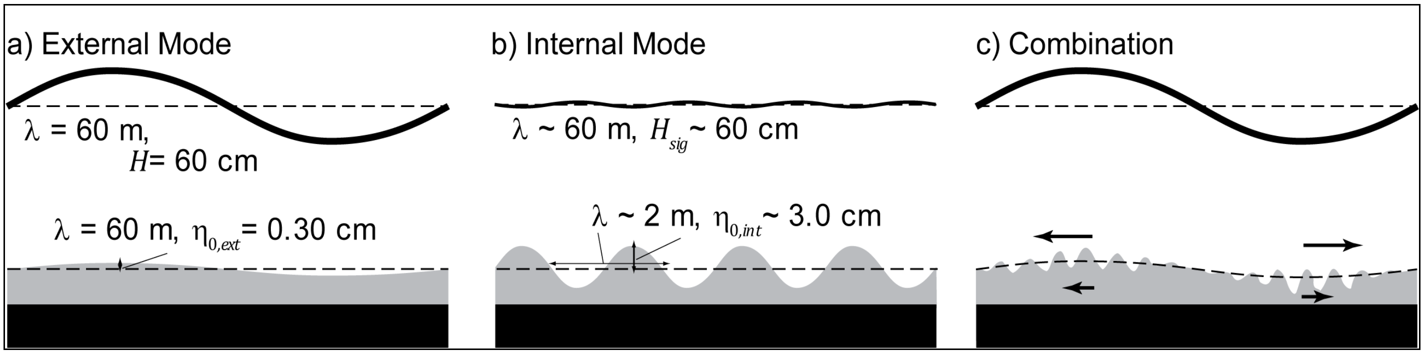


Figure 3. Schematic diagram of the two layer system showing: a) the external wave mode with the same frequency and wavelength for both the air-water and water-mud interface waves; b) the internal wave mode with the same frequency, but much shorter wavelength for the water-mud interface waves, and c) the combination of the two. The arrows in panel c) indicate shear across the mud water interface, which could lead to a shear instability mechanism to generate the internal mode waves in each half cycle of the surface and external more lutocline wave. These internal waves dissipate rapidly with imagery and real wave numbers of a similar magnitude and remove energy from the surface waves.

Analysis and Modeling: At Johns Hopkins University, Shen is performing direct simulation of mud flows in the bottom boundary layer in order to investigate the dynamics of wave-mud interaction at small scales and to establish a physical basis for the development of improved dissipation models for wave simulation at large scales. In these computations, the continuity equation and momentum equations in the primitive form are simulated with a hybrid pseudo-spectral and finite-difference scheme. A clustered grid is used in the vertical direction to fully resolve the boundary layer. A Bingham plastic model with viscosity regularization is employed. From the simulations, a detailed description of the unsteady, three-dimensional mud motion is obtained and the results show that there exist substantial differences in the velocity, vorticity, kinetic energy, and dissipation statistics between the two fluids. In particular, the presence of mud makes the fine vortical structures near the bottom merge to form coherent structures. In the vicinity of the bottom, dissipation rate in mud is higher with smoother distribution comparing to that in water. Away from the bottom, dissipation is larger in water with significant fluctuations.

At MIT, Yue and Liu obtained a preliminary direct comparison between BMWs predictions and available field experiments of Elgar & Raubenheimer (2008) for surface wave propagation over a sloped muddy seabed. Figure 4 shows the comparison of wave spectra as waves propagate over a distance of ~2 km from 4 m nearshore to 2 m beach zone. In BMWs, the bottom mud is modeled as a viscoelastic sea floor whose motion is described by a simple mass-spring-damper system and fully coupled with surface wave motion. The comparison indicates that linear BMWs (with direct linear dissipation) is capable of predicting the attenuation of long waves with good agreement with field measurement, but is not robust for short waves. Nonlinear BMWs (with indirect nonlinear dissipation) improves the prediction of short wave dissipation and gives better agreement with field measurement. We must note that for robust BMWs applications, much more calibration and parameterization of the viscoelastic mud model need to be carried out by comparisons to laboratory and field measurements.

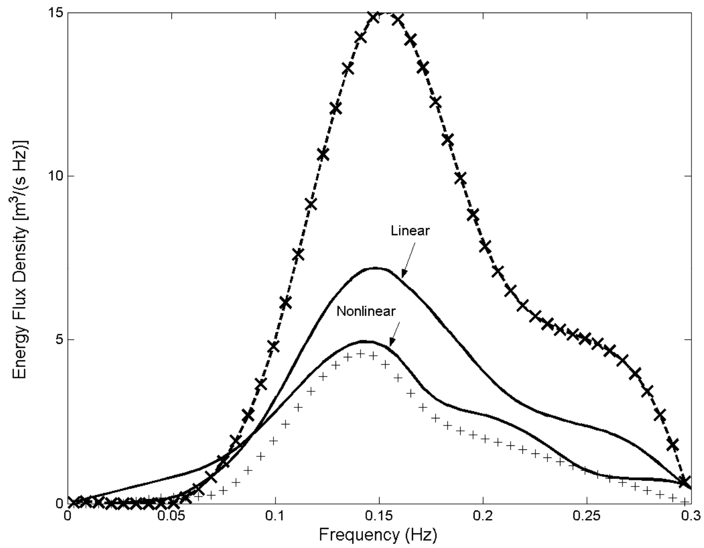


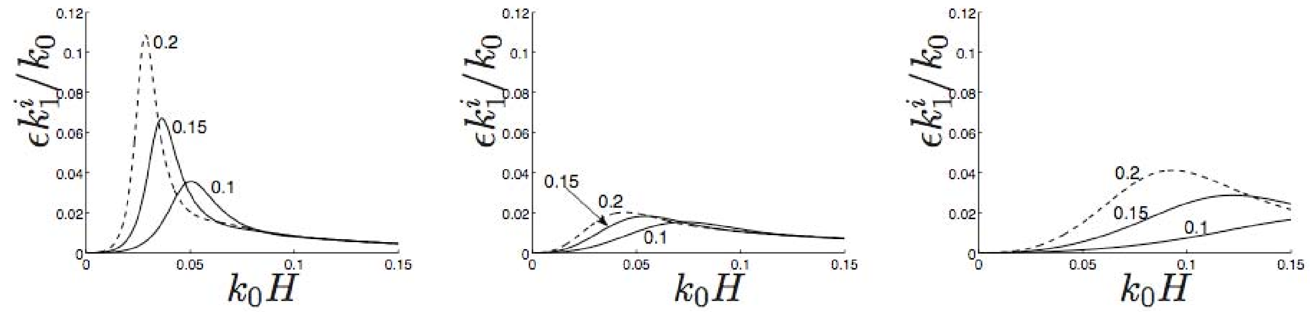
Figure 4. Comparison of wave spectrum evolution between BMWs predictions and field measurements of Elgar & Raubenheimer (2008) for ocean surface wave propagation over a muddy sea floor from 4m nearshore to 2m beach zone off Louisiana coast. The plotted lines are the field measurements at nearshore (x) and beach (+); and linear and nonlinear BMWs predictions at nearshore (dash line) and beach (solid line).

Mei at MIT uses a more complex model of mud by assuming a generalized constitutive model

$$\sum a_n \frac{\partial^n \tau_{ij}}{\partial t^n} = \sum b_n \frac{\partial^n \gamma_{ij}}{\partial t^n} \sum a_n \frac{\partial^n \tau_{ij}}{\partial t^n} = \sum b_n \frac{\partial^n \gamma_{ij}}{\partial t^n}$$

As the fluid-mud layer is usually very much thinner (d<0.5 m) than the water layer depth h above, we have assumed $h>>d$ and A where A is the characteristic amplitude of the surface waves. Based on experimental evidence the viscosity of mud is far greater than that of water, we treat water as inviscid. As the damping distance is much greater than a wave length and the swell frequency is much shorter than that of the infragravity waves, we employ a multi-scale perturbation method to analyze the interaction between the visco-elastic fluid-mud and small-amplitude waves. It is shown that at the leading order and within a short distance of a few wavelengths, wave pressure from above forces the mud motion below. Over a much longer distance, waves are modified by the accumulative dissipation in mud. At the next order, infragravity waves due to radiation stresses are affected indirectly by mud motion through the slow modulation of the short waves. Explicit results are obtained for a wave train entering a semi-infinite region of muddy bed. Mean set down and bound long waves are found to attenuate with the short waves, and free long waves can be radiated from the junction. Finally a slow streaming of mud is found to complete the second order analysis.

Typical results for Hangzhou Bay fluid mud of several concentrations ϕ are shown in Figure 5. For waves entering a semi-infinite region of muddy seabed, the change of mean set down and bound long waves due to damped short waves are examined. Free long waves are shown to radiate from the edge of the muddy bed without significant damping.



(a) Data set A $\phi = 0.20$ (b) Data set A $\phi = 0.24$ (c) Data set A $\phi = 0.34$

Figure 5. Damping coefficient for three depth ratios d/h= 0.1, 0.15, 0.2. Data set A for Hangzhou Bay mud with larger solid fractions: φ = 0.20, 0.24, 0.34

Laboratory – Two series of experiments are ongoing. The first involves the use of a water/mud tank mounted on a shaker table. The tank of water with mud at the bottom is oscillated for several minutes to build up a wave system in the tank and to allow transients to die out, and then the tank is stopped and the damping of the waves measured with time. Damping values were found to be very small for cases where the mud has consolidated over long times. Our new protocol for these experiments is to agitate the mud prior to testing, simulating an extreme storm event, such that the lutocline extends to the free surface. We have found, by examining the damping as a function of time elapsed post agitation, that the wave damping increases as the lutocline decreases from its maximum of the total water depth to about 5% of the depth; thereafter the damping decreases very slowly (over days) towards its pre-agitation state (Dalrymple and Nouri, 2008); this seems to be the same as found in the field. Rheological samples of the lutocline show that the viscosity of the mud increases faster than the shear modulus (elasticity) as the lutocline thickness decreases and consolidates.

Experiments in the large wave tank are being conducted over a mud patch that is 10 m long and 10 cm thick. Storm sequences are being run with rapidly increasing waves at the beginning of the run to generate the lutocline and then slow decrease in wave height, again simulating a storm event.

IMPACT/APPLICATIONS

The results of this combined field/laboratory/theory/modeling effort will be field and lab data for model verification and testing and models for the propagation of water waves over regions of bottom mud. The dissipation due to a variety of mechanisms will be in the models; however, the most likely mechanisms will be determined from the field experiments. Laboratory experiments will provide data to elucidate the mechanisms of energy transfer from the waves to the sediment.

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